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Foot progression angle and the knee adduction moment: a cross-sectional investigation in knee osteoarthritis[1]

D. J. Rutherford M.Sc. (P.T.), Physiotherapist†‡, C. L. Hubley-Kozey Ph.D., Professor†‡*, K. J. Deluzio Ph.D., Associate Professor‡§, W. D. Stanish M.D., Professor|| and M. Dunbar M.D., Ph.D., Assistant Professor‡||

† School of Physiotherapy, Dalhousie University, Halifax, Nova Scotia, Canada

‡ School of Biomedical Engineering, Faculty of Engineering, Dalhousie University, Halifax, Nova Scotia, Canada

§ Department of Mechanical Engineering, Queens University, Kingston, Ontario, Canada

|| Department of Surgery, Division of Orthopaedics, Dalhousie University, Halifax, Nova Scotia, Canada

Summary

Objective: To test the hypothesis that an association exists between the characteristics of the knee adduction moment and foot progression angle (FPA) in asymptomatic individuals and those with mild to moderate and severe knee osteoarthritis (OA).

Design: Fifty asymptomatic individuals, 46 patients with mild to moderate and 44 patients with severe knee OA were recruited. Maximum knee adduction moment during late stance and principal component analysis (PCA) were used to describe the knee adduction moment captured during gait. Multiple regression models were used for each of the three group assignments to analyze the association between the independent variables and the knee adduction moment.

Results: FPA explained a significant amount of the variability associated with the shape of the knee adduction moment waveform for the asymptomatic and mild to moderate groups ($P < 0.05$), but not for the severe group ($P > 0.05$). Walking velocity alone explained significant variance associated with the shape of the knee adduction moment in the severe OA group ($P < 0.05$).

Conclusion: A toe out FPA was associated with altered knee adduction moment waveform characteristics, extracted using PCA, in asymptomatic individuals and those with mild to moderate knee OA only. These findings are directly implicated in medial knee compartment loading. This relationship was not evident in those with severe knee OA.

Key words: Knee osteoarthritis, Foot progression angle, Gait analysis, Knee adduction moment, Principal component analysis.

The occurrence of osteoarthritis (OA) is speculated to rise as the average age of the North American population increases[1–4]. Although many joints in the lower extremity may be implicated, the incidence of symptomatic knee OA appears to be most frequent[1]. Knee OA is a leading cause of chronic disability in the older adult population[5]. Those with advanced OA require assistance with daily activities, incur greater economic stress and contact health care professionals with a greater frequency[6,7]. The urgency in understanding pathomechanical factors related to the development and progression of knee OA is increasing. These factors are important for the continued development and evaluation of knee OA management strategies where non-invasive treatments for knee OA are a major health care need[8].

The loading environment of the tibio-femoral joint surfaces during dynamic movement is considered as an important factor in the onset and subsequent progression of the articular cartilage and periarticular structure degeneration characteristically seen in OA[9,10]. During gait, studies show that the majority of weight-bearing compressive load is transferred through the medial compartment[11,12]. Biomechanically, the net external knee adduction moment has been characteristically defined as a dynamic feature of gait associated with medial knee compartment compressive loading[2,13–15].

Reducing the knee adduction moment has been one strategy in the prescription of non-invasive intervention. Valgus bracing and lateral heel wedges have been shown to reduce the magnitude of the knee adduction moment during gait[16–20]. Gait modifications have also been suggested. A reduced walking velocity is associated with a reduction in the peak magnitude of the knee adduction moment[21,22]. Within a theoretical biomechanical framework, a toe out foot position also reduces the knee adduction moment through a mechanism of reducing the moment arm length of the net ground reaction force (GRF) vector with respect to the knee joint center in the frontal plane[15,23]. This occurs predominantly during the second half of the stance phase, when the net GRF vector is acting through the forefoot[24]. Capturing the magnitude of the late stance knee adduction moment has been based on a discrete measure of the

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*Address correspondence and reprint requests to: Dr Cheryl L. Hubley-Kozey, School of Physiotherapy, Dalhousie University, 5869 University Avenue, Halifax, Nova Scotia, Canada B3H 3J5. Tel: 1-902-494-2635; Fax: 1-902-494-1941; E-mail: clk@dal.ca

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second peak[23−27]. Significant correlations have been found between toe out angle and a reduction in the late stance knee adduction moment, ranging from 0.40 to 0.67 in asymptomatic individuals and those with a wide range of knee OA disease severity[23,24,27]. As a toe out foot progression angle (FPA) reduces the magnitude of the knee adduction moment, knee OA progression may also be affected. Recently, Chang *et al.* found that the odds of medial OA progression were less in individuals who ambulate with a greater degree of toe out FPA during gait[28]. These findings provide support for the potential use of a toe out gait modification as a strategy in non-invasive knee OA management.

The difficulty with reports of an altered peak moment during late stance is the accuracy of defining this feature in all of the knee adduction moment waveforms. Hurwitz *et al.* found that 29% of asymptomatic individuals and 52% of subjects with knee OA did not have a definitive second peak[27]. Recent work has revealed the importance of looking at the overall adduction moment throughout stance rather than a single discrete value[22,29]. Consequently, additional waveform analytical techniques in combination with discrete measures have the potential to provide further insight into the relationship between FPA and the knee adduction moment.

Various techniques exist to capture amplitude and temporal gait waveform information. Cluster analysis, neural networks and wavelet analysis have been used to study gait waveforms[30,31,32]. Both amplitude and temporal waveform characteristics can be captured through principal component analysis (PCA)[33−36]. PCA is a multivariate statistical technique used to linearly transform a group of correlated variables (i.e., knee adduction moment waveforms), summarizing the most important information in the data set[37]. The principal components have been presented in the literature and while they are mathematical representations, they have been interpreted to represent features of the original gait waveform data[22,33,34,36,38−40]. This analysis technique has been successfully implemented in the study of kinematic and kinetic gait variables in asymptomatic control and symptomatic knee OA groups[22,33,34,36,38,40].

Studies investigating the association between FPA and the knee adduction moment have included asymptomatic individuals, individuals with specific medial compartment mild to moderate knee OA and also groups of individuals with various severities of knee OA[15,23−28]. To our knowledge, no study has quantified if cross-sectional differences exist in the association between FPA and knee adduction moment as it relates to sub-populations of individuals with knee OA. Secondly, studies that have investigated the association between FPA and knee adduction moment have used discrete variable analysis techniques (peaks) to examine the characteristics of the knee adduction moment and their association to FPA[23−27]. While relationships have been reported for peak measures, the present study focused on an evaluation of the entire knee adduction waveform in an attempt to better understand whether this modification affects the medial joint loading throughout the gait cycle.

The purpose of this cross-sectional study was to determine whether an association exists between the characteristics of the knee adduction moment and the FPA, and whether the association was different between asymptomatic individuals, those with mild to moderate and those with severe knee OA. Both discrete variable analysis and PCA were used to extract features from the knee adduction moment waveform.

Methodology

SUBJECTS

Subjects with knee OA were recruited from the Orthopedic and Sports Medicine Clinic of Nova Scotia and the Capital District Health Authority. Asymptomatic subjects were recruited from the general community. Gait analysis was completed at the Dynamics of Human Movement Laboratory, Dalhousie University, Halifax, Nova Scotia between 2001 and 2006. These subjects were grouped into asymptomatic, mild to moderate and severe knee OA categories. Functional testing, radiographical findings evaluated through the Kellgren−Lawrence (KL) criteria (0 = normal, 1 = possible osteophytic lipping, 2 = definite osteophytes and possible joint space narrowing (JSN), 3 = moderate and/or multiple osteophytes, definite JSN and possible bony attrition, 4 = large osteophytes, marked JSN, severe sclerosis and definite bony attrition) and surgical intervention were used in developing the knee OA group classification[41]. More specifically, asymptomatic subjects presented with no known lower extremity pathology and no lower extremity injuries within the past 6 months. Subjects with mild to moderate knee OA were included with a KL score of I−III, predominant medial compartment involvement (lateral JSN score < medial JSN score) and had to complete all components of the functional activity criteria. This included the following: (1) ability to walk one city block, (2) reciprocally ascend and descend 10 stairs and (3) jog 5 m. The radiographic criteria have been previously utilized as a classification of mild to moderate knee OA[22,26,29]. For the severe group, all subjects were unable to complete the functional activity criteria and completed gait analysis within 1 week prior to their total knee replacement surgery. The medial tibio-femoral compartment was predominantly involved (KL scores III−IV). Subjects in all the three groups were required to be over the age of 35 years and were excluded if cardiovascular or neurological impairments were present.

GAIT ANALYSIS

Subjects were introduced to the laboratory setting and appropriate ethical and informed consent documentation was completed as per Dalhousie University Health Sciences Human Research and Capital Health District Authority Ethics review boards.

Triangular sets (triads) of active infrared emitting diode (IRED) skin surface markers were secured to the sacrum, thigh, lower leg and foot of the subject's lower extremity. Along with individually placed IRED markers on the greater trochanter, lateral epicondyle, lateral malleolus, and shoulder, eight virtual points were digitized during a standing calibration trial[22]. These points included the right and left anterior superior iliac spines, medial epicondyle of the femur, fibular head, tibial tuberosity, medial malleolus, second metatarsal and middle posterior calcaneous. The virtual points were considered invariant and referenced to the rigid body coordinate system in which they were directly associated[22]. Bone embedded anatomical coordinate systems for the pelvis, thigh, lower leg and foot were derived from the skin surface markers and digitized points[42]. IRED skin surface marker motion was captured at 100 Hz utilizing two optoelectronic motion analysis sensors (Optotrak™, Northern Digital Inc., Waterloo, Ontario, Canada). Three-dimensional GRFs were collected at 1000 Hz from an AMTI™ force plate (Advanced Mechanical Technology Incorporation, Newton, MA, USA) that was aligned to the global coordinates of the motion capture system. Signals were analog to digital (A−D) converted (16 bit, ± 2 V), synchronized and stored for later processing.

Subjects were instructed to walk along a 5-m walkway at a self-selected velocity. After three to five familiarization trials, at least three walking trials of constant velocity and correct force plate contact were collected for further data analysis.

DATA PROCESSING

The kinematic, kinetic and FPA data were processed through custom software, written in MatLab™ version 7.0 (The MathWorks, Inc., MA, USA). Kinematic and kinetic signals were digital low pass filtered (Recursive fourth order Butterworth) at a frequency cut-off of 8 and 60 Hz, respectively. Net external knee adduction moment was calculated using an inverse dynamics model which combines GRF and moment data, kinematic positional data described using the conventions outlined in Grood and Suntay, and limb anthropometrics and inertial characteristics[43−45]. The knee adduction moment waveform was time normalized to 101 data points, representing one complete gait cycle (0−100%) and presented as a normalized net external moment (N m/kg). The FPA was derived as the angle in the transverse plane between the foot vector (second metatarsal to the posterior middle calcaneous) and the lab coordinate corresponding to the line of progression. This algorithm was tested against known angles marked on the walkway force platform and an error of less than 1° was found.

ANALYSIS

For each subject, the maximum magnitude of the knee adduction moment in N m/kg during late stance was identified as the maximum value between

30 and 60% of the gait cycle. PCA was used to identify waveform features [principal components (PCs)] that together explained greater than 85% of the variance[22,34–36]. For PCA, the original waveform data of the entire group (X) was organized into a matrix [$n \times p$], where n is the total number of subjects and p indicates the 101 gait cycle data points. The mean $(\overline{X}) = [1 \times 101]$ was subtracted from the original waveform data (X) and a covariance matrix (S) [101 × 101] was computed directly from $[X - \overline{X}]$. PCA involves an eigenvector decomposition of the covariance matrix using standard notation $U'SU = L$, yielding the predominant orthogonal components (PCs) that assist to hierarchically explain the waveform variance (i.e., PC1, PC2, etc.,)[34,35]. Collectively the PCs capture the original shape and magnitude from the measured knee adduction moments. Individual PC-scores ($\text{PC-score} = [X - \overline{X}] \times U$) were computed for each subjects gait waveform. The PC-score provides a measure of how accurately the individual's gait waveform is projected on to the derived PC.

STATISTICAL ANALYSIS

Analysis of variance (ANOVA) models were implemented to test the group assignment (asymptomatic, mild to moderate, and severe) against age, body mass index (BMI), velocity and FPA. Bonferroni *post hoc* testing ($\alpha < 0.05$) was used to test all significant effects. Forward stepwise regression models ($P_{in} = 0.05$ and $P_{out} = 0.1$) were used in each of the three group assignments to analyze the independent variables (gender, age, BMI, velocity, and FPA) for association with the maximum magnitude of the knee adduction moment during 30–60% of the gait cycle and relevant PC-scores (PC1, PC2 and PC3). A total of four regression models were employed in each group. Variance inflation factors were used to assess the multicollinearity of the independent variables. The suitability of the regression model was evaluated by examining the normality of the residual histograms and the plots of the residuals against the predicted values. All statistical analyses were computed on Minitab™ V.14.

Results

A total of 140 subjects participated in the study. Table I illustrates demographic characteristics of the data set, the average walking velocity and FPA for each group. ANOVA results demonstrate significant group effects for age, BMI and velocity. Age was significantly different between the groups, BMI significantly lower in the asymptomatic group ($P < 0.001$) and those with severe knee OA walked significantly slower ($P < 0.001$) than asymptomatic individuals and those with mild to moderate knee OA. All groups walked with a similar toe out FPA as shown in Table I with no significant differences between the groups ($P > 0.05$).

KNEE ADDUCTION MOMENT

The mean knee adduction moment for each group, as a percentage of the gait cycle, is shown in Fig. 1. The asymptomatic and mild to moderate OA groups demonstrate a distinct first and second peak corresponding to approximately 18 and 50% of the gait cycle, respectively. In the severe OA group, the first peak is delayed to 25% of the gait cycle and the second peak is not easily distinguished. A definitive second peak that could be objectively defined was observed in 88% of the asymptomatic subjects, 59% of those with mild to moderate knee OA and only 30% of those with severe knee OA.

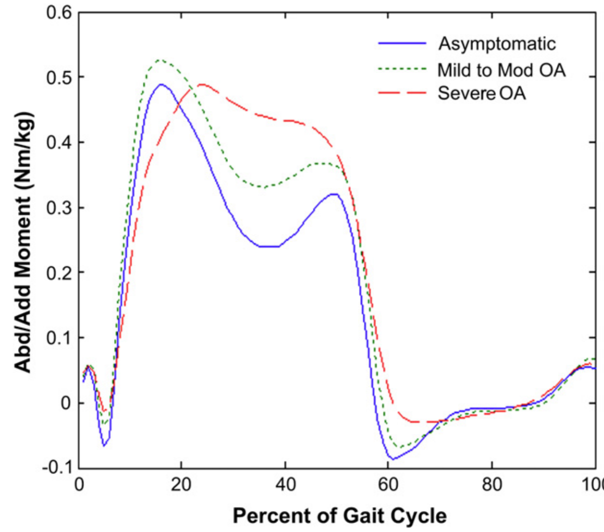

Fig. 1. The ensemble-averaged net external knee adduction moments for each group assignment. Note the biphasic pattern for the asymptomatic and moderate OA groups that was not apparent in the severe group.

PCA

Three principal components were extracted from the original data set, explaining a combined 87% of the waveform variance. PC1 explained 61% of the variance, capturing the general shape and overall knee adduction moment waveform magnitude [Fig. 2(A)]. PC2 captured the magnitude difference between the initial period of stance (approximately 15–18% of the gait cycle) and the latter period (30–60% of the gait cycle) explaining 20% of the variance [Fig. 2(B)]. PC3 explained 6% of the waveform variance, capturing the magnitude differences between early, mid and late stances [Fig. 2(C)]. The principal components and the ensemble-averaged waveforms corresponding to the 5th and 95th percentile PC-scores are shown in Fig. 2(D–E).

MULTIVARIATE REGRESSION ANALYSIS

The significant findings of the regression analysis are given in Table II. FPA, velocity, BMI, age and gender showed no significant effect in explaining the variability associated with either the maximum magnitude of the knee adduction moment during 30–60% of the gait cycle or the PC1 scores for asymptomatic and mild to moderate knee OA groups. Both velocity and FPA explained significant amounts of variability in the PC2 scores, where only FPA explained significant amounts of variability in the PC3 scores in both of these groups. Velocity was found to explain a significant amount of variability in the knee

Table I
Demographic characteristics of the population groups

Group (SD)	N	Age, years (SD)	Gender (M/F)	BMI, kg/m^2 (SD)	Velocity, m/s (SD)	FPA (+) = toe out, deg (SD)
Asymptomatic	50	53 (10)*	32/18	26 (4)*	1.35 (0.18)†	7.3 (5)
Mild to moderate OA	46	60 (9)†	20/26	31 (5)	1.28 (0.22)†	8.0 (5)
Severe OA	44	67 (8)	20/24	32 (5)	0.91 (0.24)	7.5 (5)

*Significantly different from mild to moderate and severe OA groups ($P < 0.05$).
†Significantly different from severe group ($P < 0.05$).

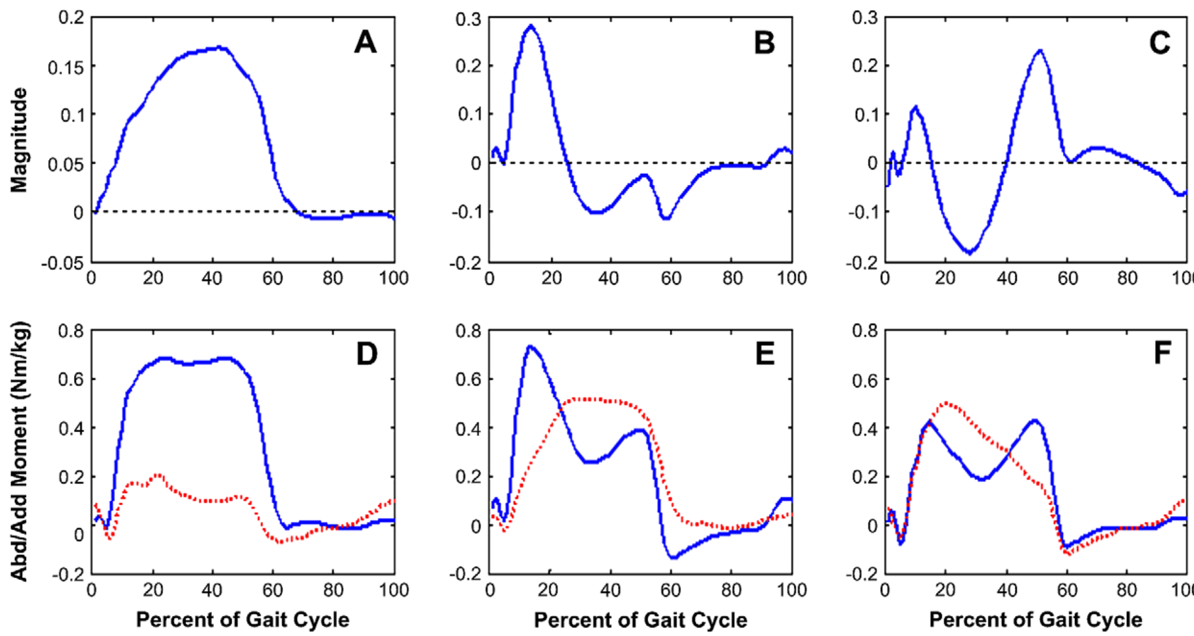

Fig. 2. PCA: (A) PC1 captured the overall magnitude and shape of the knee adduction moment waveform and explained 61% of the variance in these waveforms, (B) PC2 captured the difference in magnitude between early and late stances, (C) PC3 captured the unloading in mid stance phase. The 5th and 95th percentile knee adduction moment waveforms associated to the individual PC-scores are shown for PC1 (D), PC2 (E) and PC3 (F).

adduction moment during 30–60% of the gait cycle, PC1 and PC2 scores in the severe OA group.

Discussion

This study provides evidence, through the use of PCA, that a toe out FPA is associated with changes in the temporal pattern of the knee adduction moment in particular the biphasic representation of this moment during stance phase of gait. The results illustrate that these relationships were dependent on the presence of and the severity of knee OA.

A radiographic and clinical/functional patient selection criterion was utilized to determine group classification. Brandt *et al.* found that radiographs alone are not sufficient to determine the extent of knee OA pathology[46]. Current classification criteria combine radiographic features and clinical symptomology; however, functional activities have not been explored[47]. Our selection criterion provided three distinct groups with the two OA groups clearly distinguishable based on function rather than KL scores alone. This functional difference was in part verified by the significant reduction in walking velocity for the severe group compared to the moderate OA or asymptomatic groups. Walking velocity is associated with function and this temporal gait characteristic is typically lower in those with knee OA, compared to asymptomatic controls[22,29].

While this study focused on the relationship between FPA and the knee adduction moment, age, gender, BMI and walking velocity were included as independent variables to contextualize FPA within a framework of factors that may influence the knee OA disease process and biomechanical gait variables[22,38,48,49]. Age, gender and BMI did not explain significant levels of variance in the characteristics of the knee adduction moment. In contrast, walking velocity was associated with the PC2 scores for all three groups, a finding consistent with a previous study that evaluated gait biomechanics using PCA in moderate OA[22]. Thus, those with faster walking velocities had a higher knee adduction magnitude early in stance compared to the magnitude late in stance, suggesting that impact loads were much higher than the loads prior to toe off. The waveforms for the high and low PC2 scores in Fig. 2(E) illustrate this characteristic. Velocity was the only variable that explained any variance in the severe OA group knee adduction moment characteristics. An increased velocity was associated with a decrease in maximum magnitude during late stance, a decrease in overall magnitude (PC1) and an increase in the difference between early and late stance magnitudes (PC2). Consequently those in the severe group that walked with a faster velocity had a more typical knee adduction moment waveform, but FPA did not modify this relationship. In addition to the velocity effect, the FPA

Table II
Multiple regression analysis of knee adduction moment characteristics

Dependent variable	Velocity		FPA		Model R^2	Model *P* value
	Coefficient	Partial R^2	Coefficient	Partial R^2		
Asymptomatic						
PC2	1.25	0.38	0.03	0.15	0.53	0.000
PC3	–	–	−0.03	0.17	0.17	0.003
Mild to moderate						
PC2	1.43	0.28	0.05	0.35	0.63	0.000
PC3	–	–	−0.02	0.22	0.22	0.001
Severe						
30–60%	−0.31	0.15	–	–	0.15	0.009
PC1	−1.62	0.11	–	–	0.11	0.027
PC2	1.11	0.56	–	–	0.56	0.000

Only significant results are shown.

adopted during gait was associated with characteristics of the knee adduction moment for the asymptomatic and moderate OA groups only.

Based on a theoretical biomechanical model and empirical data, toe out gait has been suggested to reduce the magnitude of the late stance knee adduction moment[23,24,26,27]. The pathomechanical relationship between the knee adduction moment and the medial tibio-femoral compartment load suggests that a reduction of this moment in any capacity would subsequently reduce the cumulative compressive load in the medial compartment. Consistent with previous investigations, determining the relationship between the FPA and the late stance knee adduction moment is difficult given that the second peak cannot always be distinguished[26,27]. In this study only 30% of the severe group and 59% of the moderate group had this feature. This is apparent from the average waveforms illustrated in Fig. 1. Different methods have been proposed to determine this second peak when one does not exist, however, there is no gold standard[26,27]. With the heterogeneity of our sample we chose an algorithm that captured the maximum knee adduction moment magnitude during the second half of the stance phase. While this provides us with a measure of the loading on the knee joint during late stance it cannot be compared directly to all of the previous studies that have investigated the absolute and theoretical second peak[23,24,26,27]. It is also important to note that the differences among studies with respect to the methodologies employed indicate that the peak could in fact occur at different points throughout the gait cycle[23,24,26,27]. Presumably, where the peak occurs within the gait cycle would have an effect on interpretation of the results and the clinical importance. To address this problem of identifying discrete points, Thorpe[29,50] calculated the area under the curve to represent the overall magnitude of the knee adduction moment during stance phase. Consistent with Thorpe's approach, the PCA employed in the present study allows us to quantify magnitude using the entire waveform, and in addition can capture the dynamic features of the waveforms associated with specific phases of the gait cycle.

The PCA findings provide evidence to support that the variance in the knee adduction moment explained by the FPA adopted during gait differs between group assignments. PC1 captured the overall magnitude and general shape of the waveform as illustrated in Fig. 2(A) and the represented high and low scores in Fig. 2(D). In asymptomatic subjects and both OA groups, FPA was not associated with the overall magnitude of the adduction moment (PC1), suggesting that a toe out gait pattern does not reduce the overall load on the medial compartment. While this may appear to be inconsistent with previous reports, no study has measured overall magnitude, they all reported a peak measure from a defined portion of the waveform[23,24,26,27].

PC2 acted as a difference operator between the magnitude of the initial and late stance periods as illustrated in Fig. 2(B). This characteristic is consistent with previous work that has investigated the knee adduction moment during knee OA gait with PCA[22,38]. FPA explained significant levels of variability associated with PC2 in asymptomatic subjects and those with mild to moderate knee OA. Individuals within these group classifications who walked with a greater toe out angle had a late stance knee adduction moment magnitude that was reduced compared to the initial stance magnitude. Figure 2(E) illustrates that a high PC2 score has a high early stance magnitude compared to late stance magnitude, therefore impact loading is higher than the loading during push off. These findings for the most part are consistent with reports of a reduced knee adduction moment during late stance[15,23,24]. Thus, toe out gait is associated with reduced loading during push off, but only in asymptomatic controls and those with mild to moderate symptoms. How important this reduction is has not been previously established, but it has only been speculated that any reduction in medial joint loading throughout stance is positive.

FPA also explained a significant amount of variation in the PC3 scores of asymptomatic individuals and those with mild to moderate knee OA. A prolongation of a heightened moment during the transition from initial stance to mid stance was associated with a greater toe out angle. This suggests that while a reduction in the late stance moment (PC2) occurred when individuals toe out, PC3 captured a prolonged joint loading during the mid stance transition. This finding is novel and suggests that adopting a toe out FPA is associated with a reduced ability to unload the medial tibio-femoral compartment.

In the severe knee OA group, the relationship between the FPA and the PC2 and PC3 scores that was apparent in asymptomatic individuals and those with mild to moderate knee OA was not found. Considering only 30% of the individuals in the severe knee OA group had a biphasic knee adduction moment (i.e., an identifiable first and second peak), this result is not surprising. It is evident that this group does not unload the knee adduction moment during mid stance (Fig. 1). Therefore the benefit of this gait modification for this group is questionable.

The interpretation of the results needs to be done within the limitations of the study. Firstly, as with all cross-sectional designs we are unable to extrapolate our findings directly to the effect FPA has on disease progression. This would be better evaluated through longitudinal design[28]. Secondly, we did not study the kinetic effects of voluntarily modifying the FPA on the entire lower extremity, limiting our ability to imply that a causative relationship exists between FPA and the knee adduction moment. Further work is required to evaluate this entity, and to establish applicability in clinical management. Thirdly, as previously mentioned, the discrete variable analysis was intended to capture the maximum knee adduction moment during late stance, and not specifically to identify the second peak. Within these limitations, the analysis provides us with additional information that adds to our understanding of the relationships that exist between FPA and the magnitude and temporal characteristics of the knee adduction moment.

PCA has previously been implemented during gait study[22,34,36,38]. The success of this multivariate statistical technique is limited by interpretation of the principal patterns since they are mathematical representations of the original knee adduction moment waveforms. Where discrete variables capture a point in the time domain of the waveform, PCA assists to explain both magnitude and shape over the entire gait cycle[27,34], thus an examination of the dynamic characteristics for biomechanical interpretation. Although discrete values are unable to be captured through PCA, the PC-scores provide relative measures of similarity between the principal components and original data. This is clearly represented in Fig. 2.

Conclusion

A functional criterion was implemented, in combination with radiographic findings, to differentiate the mild/moderate classification from the severe OA group. The maximum magnitude of the knee adduction moment during mid to late stance and the overall magnitude of the knee adduction moment (PC1) were not related to the FPA adopted during gait for any of the three groups tested. FPA explained a significant amount of the variance in the principal component that captured a reduction in the knee adduction moment during late stance compared to early stance (PC2) in asymptomatic individuals and those with mild to moderate knee OA. A toe out FPA, however, was also associated with a prolonged loading response during the transition from initial to mid stance in these two groups (PC3). Therefore toe out FPA was associated with a reduced ability to unload the knee joint during mid stance. These two findings were not supported in those with severe knee OA. FPA did not explain a significant amount of the variability in the PC2 and PC3 scores indicative of a lack of the biphasic shape in the severe group.

The clinical implication of these findings are that in asymptomatic individuals and those with mild to moderate knee OA, a toe out FPA was associated with alterations in the knee adduction moment, directly affecting the medial compartment compressive load, where this relationship was not found for those with severe knee OA.

Conflict of interest

The authors acknowledge that there are no conflicts of interest pertaining to this manuscript.

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